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Thermal pretreatment of wood (Lauan) block by torrefaction and its influence on the properties of the biomass

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A R T I C L E I N F O

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A B S T R A C T

The purpose of this study is to investigate the torrefaction behavior of woody biomass (Lauan) blocks and its influence on the properties of the wood. Three different torrefaction temperatures of 220, 250 and 280 °C, corresponding to light, mild and severe torrefactions, and four torrefaction times of 0.5, 1, 1.5 and 2 h were considered. After analyzing the torrefied woods, it was found that the torrefaction temperature of 280 °C was able to increase the calorific value of the wood up to 40%. However, over 50% of weight was lost from the wood. The grindability of the torrefied wood could be improved in a significant way if the torrefaction temperature was as high as 250 °C and the torrefaction time longer than 1 h. Therefore, the torrefaction temperature of 250 °C along with the torrefaction time longer than 1 h was the recommended operation to intensify the heating value and grindability as well as to avoid too much mass loss of the wood. This study also suggested that over 50% of the reacted wood was converted into condensed liquid. The main components in the liquid were monoaromatics; little amount of heterocyclic hydrocarbons were also obtained from the torrefactions, especially at the torrefaction temperature of 280 °C.

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1. Introduction

On account of the atmospheric greenhouse effect, environmental pollution and rapid shortage of fossil fuels encountered currently, the interest in developing renewable energy has received a considerable deal of attention for years. To date, renewable energies which are being developed include solar, wind, geothermal, hydroelectric, marine and biomass energies [1,2]. Among these renewable energies, biomass energy or bioenergy is the largest and the most important one in that it has been employed worldwide, including in underdeveloped, developing and developed countries [3]. By capturing solar energy and combining water and carbon dioxide through photosynthesis, biomass is generated. After biomass is burned, the chemical energy stored in the material is converted into thermal energy and carbon dioxide is released into the atmosphere. By virtue of the cycle of carbon between the atmosphere and biomass, it has been considered as a carbon-neutral fuel [4,5]. Consequently, in contrast to fossil fuels, consuming biomass as a source of energy is beneficial to the reduction of greenhouse gas emissions, the energy security and the sustainable development of the environment.

When biomass is used as a solid fuel or feedstock, a number of methods can be employed to improve its efficiency of utilization. These methods include dewatering and drying [6,7], size reduction or pulverization [8–10] and pelletization or densification [11–13]. The function of dewatering and drying is to remove moisture content in biomass, thereby increasing the heating value of the material. Size reduction or pulverization enlarges the biomass surface per unit mass; this is conducive to the reaction of the material when burning, gasification or pyrolysis is performed. In regard to pelletization or densification, it substantially reduces the volume of biomass. This process makes the storage and delivery of biomass easier. Aside from the conventional pretreatments described above, another noticeable method for improving biomass as a fuel or feedstock is torrefaction.

Unlike the aforementioned physical processes, torrefaction is a kind of thermal pretreatment process where raw biomass is heated in an inert or nitrogen atmosphere with the temperatures of 200–300 °C [14]. The conditions of fuel processing with torrefaction are similar to those of pyrolysis but the temperatures of the latter are usually between 350 and 650 °C [15]. Therefore, torrefaction has been thought of as a mild pyrolysis process [16,17]. In

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general, raw biomass possesses high moisture and relatively low energy density. Moreover, it is hard to pulverize woody biomass and the durability of raw biomass is low. In recent years, a number of studies on torrefaction have been performed to recognize the influence of torrefaction on the properties of biomass. It is found that after experiencing torrefaction, the properties of biomass are improved to a great extent. The advantages accompanied by torrefaction include (1) the higher heating value or energy density [16–18], (2) the lower O/C ratio and moisture content [19–22] and (3) the easier storage, grindability, reactivity and delivery [23,24] of biomass. Besides, the properties of torrefied biomass are more uniform compared to those of raw biomass.

When biomass is developed for bioenergy, wood is one of the important and commonly used fuels. It has been extensively burned directly or co-fired with coal for the purpose of getting heat and power [25,26]. Wood is a bio-composite which is mainly formed by the combination of three cell wall polymers of cellulose, hemicellulose and lignin [27]. While wood is torrefied, some light volatiles are liberated due to a high-temperature environment [28]. The high-temperature environment also causes the thermal degradation of the three cell wall polymers. As a result, the properties of wood change significantly. For example, the hygroscopic nature of raw biomass is changed to be hydrophobic.

As a matter of fact, when wood is torrefied, all reaction products are presented in three phases [28], consisting of a partly carbonized solid product or charcoal (bio-char), a condensed liquid and a non-condensable gas mixture, including CO, CO_2 and small amounts of hydrogen and methane. In order to provide a comprehensive insight into the torrefaction characteristics of woody biomass, the present study aims to investigate the formation of torrefied wood and condensed liquid from wood (Lauan) block. The influence of the thermal pretreatment on its properties will be addressed. A standard procedure for evaluating the grindability of torrefied wood blocks will be developed as well. On the other hand, an examination of literature indicates that most of the research was focused on the solid phase and relatively little research has been performed on the liquid phase. Therefore, the liquid yield and components in the produced liquid will also be analyzed.

2. Experimental

2.1. Reaction system

A schematic of the experimental system is shown in Fig 1. The system, as a whole, was made up of a nitrogen steel cylinder, a reactor and a liquid collection unit. The nitrogen steel cylinder was used to supply nitrogen as a carrier gas for providing a non-oxidizing or torrefaction environment. The volumetric flow rate of nitrogen was controlled by an electronic mass flow controller (KD-4000) in conjunction with a controller readout (Brooks 5850E). The reactor comprised a quartz reaction tube and a heater (or electrical furnace). The tested wood blocks were packed in the tube for torrefaction and the heater was used to elevate and sustain the reaction temperature. The liquid collection unit was composed of two conical flasks; the first one was for liquid collection and the second one for cleaning exhaust gas.

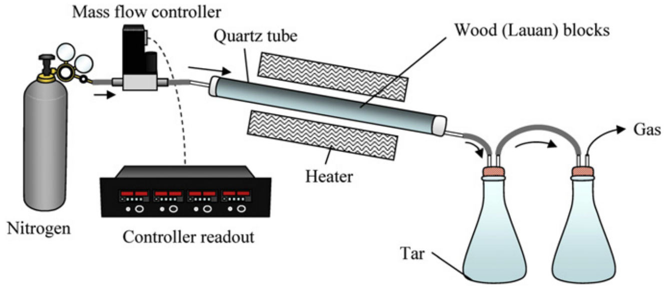


Fig. 1. A schematic of the experimental system.

2.2. Experimental procedure

The tested wood was Lauan. Before experiments were carried out, the wood was cut into blocks with the dimension of 10 × 15 × 40 mm. Then, the biomass samples were dried in an oven with the temperature of 105 °C for 24 h to provide a basis for experiments. In each run, three blocks of wood with total mass of 9 g (±5%) were placed in the reaction tube. After the wood blocks were in the tube, they were heated in the reactor at a heating rate of 30 °C min^{-1} until the desired torrefaction temperature was reached. Then, the samples were torrefied for a given time period. While the wood blocks were treated, nitrogen with the flow rate of 50 cc min^{-1} was continuously blown into the reaction tube to keep the system in an inert environment and remove volatile products from the reactor. Soon after the gas mixture left the reactor, they were cooled to enable us to condense and collect liquid in the collection unit. Prior to performing experiments, the reaction system was leak tested to ensure the measurement quality. In addition, the instruments for analyzing the raw and torrefied woods were periodically calibrated to guarantee the accuracy of the analysis. The experiment under any given condition was usually carried out more than twice. The results were fairly uniform between each run and the relative error was less than 5%.

2.3. Material analysis

The proximate, elemental (ultimate) and fiber analyses as well as the higher heating value (HHV) of the raw material are listed in Table 1. The proximate analysis of the wood was performed in accordance with the standard procedure of American Society for Testing and Materials (ASTM E870-82). The elemental analysis was carried out using an elemental analyzer (Vario EL III). In regard to the fiber analysis, hemicellulose, cellulose and lignin were analyzed, following the method adopted in a previous study [29]. In brief, the neutral detergent fiber (NDF) was determined first. Then, the acid detergent fiber (ADF) was determined. From the NDF and ADF, hemicellulose could be obtained. Furthermore, one could get cellulose after the ADF was treated by concentrated H_2SO_4.

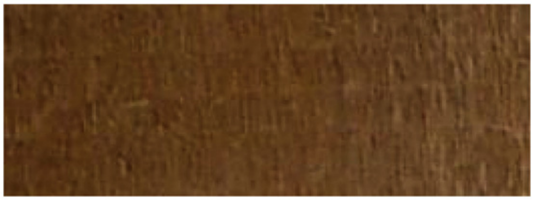
Table 1
Proximate, elemental and fiber analyses as well as heating value of the tested wood (Lauan).

Analysis	Value
Proximate analysis (wt%)	
Moisture	7.45
Volatile matter (VM)	75.08
Fixed carbon (FC)	17.22
Ash	0.25
Elemental analysis (wt%, daf*)	
C	48.77
H	6.77
N	0.10
O	44.36
Fiber analysis (wt%)	
Hemicellulose	15.74
Cellulose	40.49
Lignin	43.77
HHV (MJ/kg, db**)	20.41

* Dry ash free.
** Dry basis.

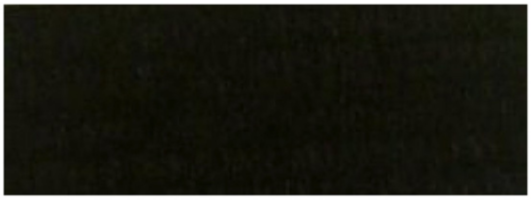
Eventually, the content of lignin was obtained once the ash was measured. The HHV of the sample was measured by a bomb calorimeter (IKA C2000 Basic). The non-isothermal thermogravimetric analysis (TGA) with the heating rate of 20 °C min^{-1} was executed by a thermogravimetry (PerkinElmer Pyris 1 TGA) where the temperature ranged from 25 to 800 °C. In each TGA, 2 mg of sample was tested where the flow rate of carried gas (Air) was 20 cc min^{-1}. The micrographs were taken using a scanning electron microscope (FEI Quanta 200). A gas chromatography (Agilent 6890) and a mass spectrometer (Agilent 5973) were employed to analyze the components in the condensed liquid. In the GC-MS analyses, the species with the molecule weight less than 45 were not detected. In addition, emphasis of the compounds in the condensed liquid was placed on aromatics. Therefore, some common encountered species, such as lactic acid, formic acid, methanol and water were not measured. To evaluate the grindability of a torrefied sample, it was introduced into a four-blade cracker. From a number of tests using three different sieves (i.e. 100, 200 and 325 mesh), it was found that the rotation speed of 24,000 rounds per minute (rpm) for 1 min was a proper procedure to evaluate the grindability by dividing the ground samples into four size regimes. They were: (a)

a Raw wood (Lauan)



b Torrefied wood at 220°C

c Torrefied wood at 250°C



d Torrefied wood at 280°C

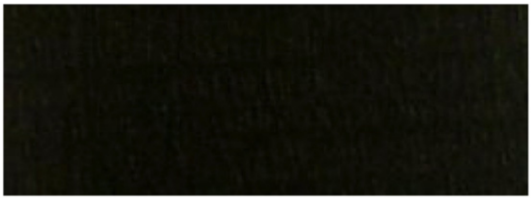
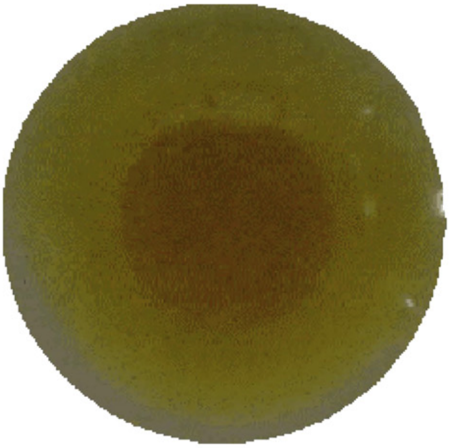
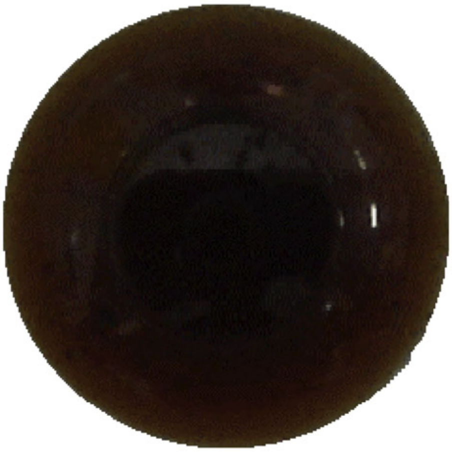


Fig. 2. Observations of (a) raw wood and torrefied wood blocks at the torrefaction temperatures of (b) 220, (c) 250 and (d) 280 °C (torrefaction time = 2 h).

a 220°C



b 250°C



c 280°C

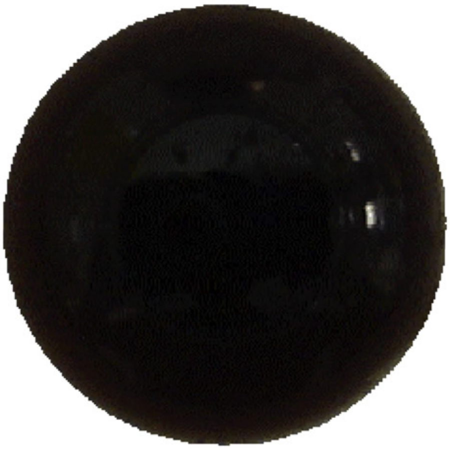


Fig. 3. Observations of condensed liquid (0.05 cc) from wood at the torrefaction temperatures of (a) 220, (b) 250 and (c) 280 °C (torrefaction time = 2 h).

No. 1 for particle size larger than 100 mesh (150 μm); (2) No. 2 for particle size between 100 and 200 mesh (75–150 μm); (3) No. 3 for particle size between 200 and 325 mesh (45–75 μm); and (4) No. 4 for particle size less than 325 mesh (45 μm). Therefore, the aforementioned method was utilized as a standard procedure to evaluate the grindability.

3. Results and discussion

Reviewing past studies [3,27,30] indicates that the torrefaction of biomass can roughly be classified into three types; one is light torrefaction, another mild torrefaction and the other severe torrefaction. Accordingly, in the present study, three different torrefaction temperatures of 220, 250 and 280 °C, which are the typical temperatures of light, mild and severe torrefactions, were considered. Meanwhile, it can be found that the torrefaction time was usually controlled within 2 h [19]. Consequently, four different torrefaction times of 0.5, 1.0, 1.5 and 2.0 h were tested. In the following discussion, the characteristics of torrefied wood and condensed liquid will be analyzed.

3.1. *Productions of torrefied wood and condensed liquid*

Fig 2 first demonstrates the observations of the raw and torrefied wood blocks at the three torrefaction temperatures (i.e. 220, 250 and 280 °C) where the torrefaction duration was 2 h. As can be seen in the figures, following the torrefactions the wood blocks change from yellow to black, stemming from the partial carbonization at the wood surface, and the color of the block surface is insensitive to the torrefaction temperature. When the condensed liquids from the 2 h torrefactions are examined, as shown in Fig 3, unlike the torrefied wood, the torrefaction temperature has a pronounced effect on the color of tars. Specifically, when the temperature is 220 °C, the color of the condensed liquid (0.05 cc) is bright yellow (Fig 3a). Once the torrefaction temperatures are 250 and 280 °C, the colors of the liquids become brown (Fig. 3b) and dark brown (Fig. 3c), respectively. This may be explained by the sensitive behavior of volatiles released from the torrefaction processes at various temperatures.

The profiles of weight loss percentage of the wood blocks at various torrefaction temperatures and times are plotted in Fig 4. As a whole, it can be seen that, within the investigated ranges of torrefaction temperature and time, the influence of the temperature on the weight loss is more profound than that of time. For the torrefaction temperature of 220 °C, the weight loss is less than 21%, regardless of what the torrefaction time is. When the wood is torrefied at 250 °C, the weight loss is in the range of 40–50%. Once the torrefaction temperature is as high as 280 °C, the weight loss is always larger than 50%. The weight loss of the wood at 220 °C is mainly due to the thermal degradation of hemicellulose in that hemicellulose is the relatively active constituent in biomass. In contrast, the weight losses of the wood from the torrefactions at 250 and 280 °C are attributed to the simultaneous reactions of hemicellulose and cellulose. Only a small portion of weight loss

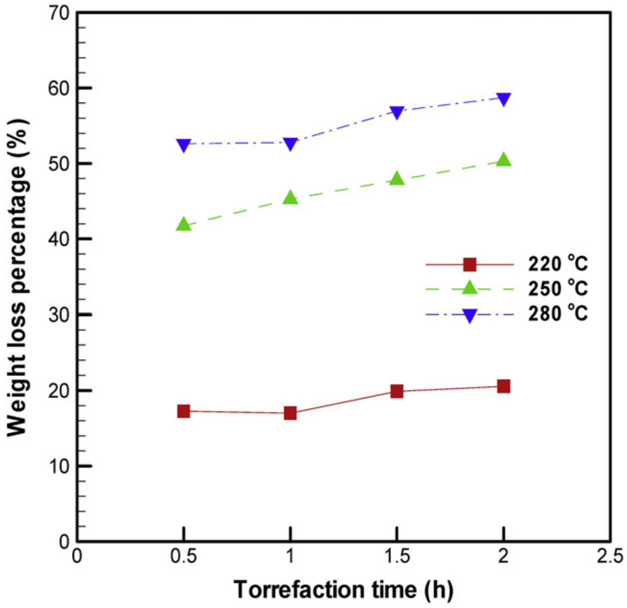


Fig. 4. Profiles of weight loss percentage of wood blocks versus torrefaction time at three different torrefaction temperatures.

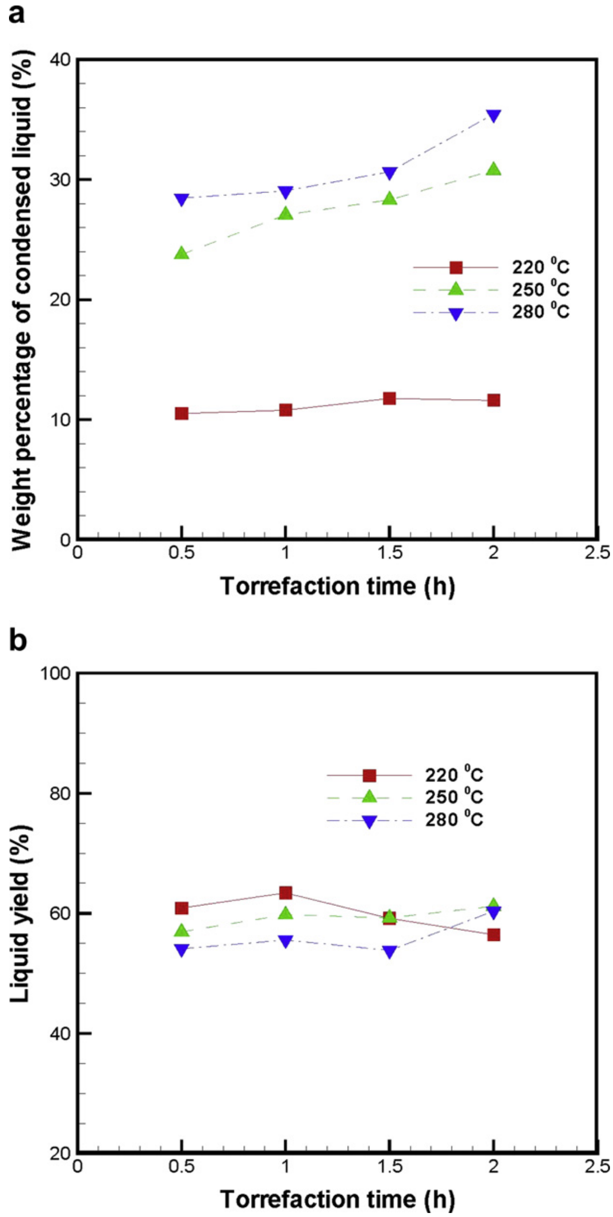


Fig. 5. Profiles of (a) weight percentage of condensed liquid from wood and (b) liquid yield versus torrefaction time at three different torrefaction temperatures.

comes from the reaction of lignin. In view of much mass of the wood being depleted from the severe torrefaction (280 °C), it is thus concluded that the torrefaction temperature of 280 °C is inappropriate for the thermal pretreatment of the wood blocks. Similar finding has also been reported from the thermogravimetric analyses of biomass powders [3].

With attention shifted to liquid formation, Fig 5a depicts that around 11 wt% of the raw wood is converted to liquid when the torrefaction temperature is 220 °C. Alternatively, corresponding to the torrefaction temperatures of 250 and 280 °C, the formation ratios of liquid from the raw wood are in the ranges of 24–31 wt% and 28–35 wt%, respectively. If one defines the liquid yield as

$$\text{Liquid yield}\ (\%) = \frac{\text{Weight of generated liquid (g)}}{\text{Weight loss of raw wood (g)}} \times 100\% \tag{1}$$

the distributions of liquid yield at various operating conditions are presented in Fig 5b. The figure suggests that the liquid yield is located between 54 and 63 wt%, implying that over 50% of the consumed wood is converted into liquid. By virtue of high content of condensable liquid contained in the product gas, this reflects that the gas stream from torrefaction should be treated by condensation to capture more energy, fuel or chemicals by recovering condensed liquid, from the perspective of practical operation.

3.2. Calorific and elemental analyses

The calorific and elemental analyses of the raw wood and the torrefied materials are provided in Table 2. The HHV of the raw wood is 20.70 MJ kg^{-1}. Once the wood undergoes torrefaction at 220 °C, the HHV is lifted to around 23.20–23.77 MJ kg^{-1}, revealing that the calorific value of the wood is amplified by a factor of 1.12–1.15. With the torrefaction temperature of 250 °C, the heating value is in the range of 26.92–28.16 MJ kg^{-1}. It follows that the energy contained in the torrefied wood is enlarged by 30–36%. Once the torrefaction temperature is further increased to 280 °C, the HHV is between 28.08 and 28.93 MJ kg^{-1}, that is, the increment in the calorific value is between 36 and 40%. Even though the calorific value is increased markedly at 280 °C, the weight loss of the wood is also pronounced, as shown in Fig 4. It is thus pointed out that the torrefaction temperature of 280 °C is inadequate to pretreat biomass. As far as the elemental analysis is concerned, Table 2 clearly reveals that the higher the torrefaction temperature, the higher the element carbon and the lower the element oxygen in the torrefied wood. This reflects that the carbonization of the wood

Table 2
Heating value and elemental analyses.

Torrefaction temperature (°C)	Torrefaction time (h)	Higher heating value, HHV (MJ/kg, db[a])	Elemental analysis (wt%, daf[a])			
			C	H	O	N
Raw wood	–	20.70	48.77	6.77	44.36	0.10
220	0.5	23.20	54.33	6.99	38.53	0.15
	1	23.23	54.91	6.85	38.07	0.17
	1.5	23.69	55.15	6.65	38.12	0.08
	2	23.77	55.65	6.25	37.97	0.13
250	0.5	26.92	64.40	6.37	29.11	0.12
	1	27.52	65.37	6.06	28.41	0.16
	1.5	27.77	65.60	5.92	28.35	0.13
	2	28.16	66.73	5.84	27.30	0.13
280	0.5	28.08	64.76	5.92	28.88	0.44
	1	28.38	65.76	5.47	28.61	0.16
	1.5	28.77	69.79	5.77	24.31	0.13
	2	28.93	70.25	5.35	24.23	0.17

[a] Dry ash free basis.

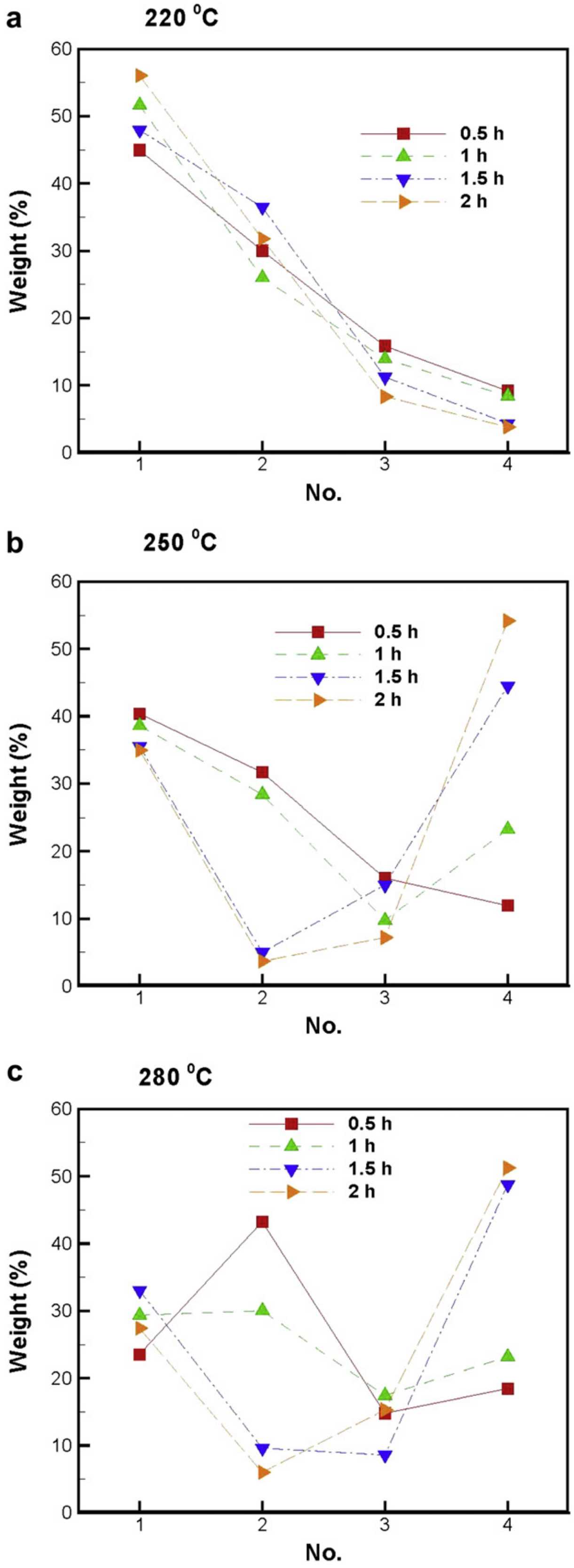
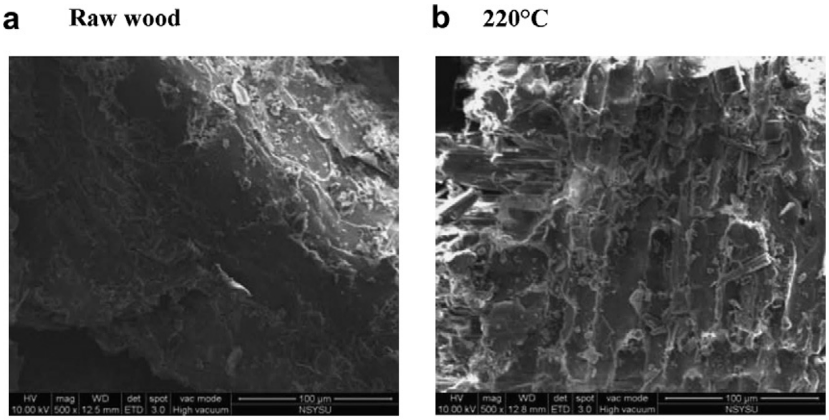


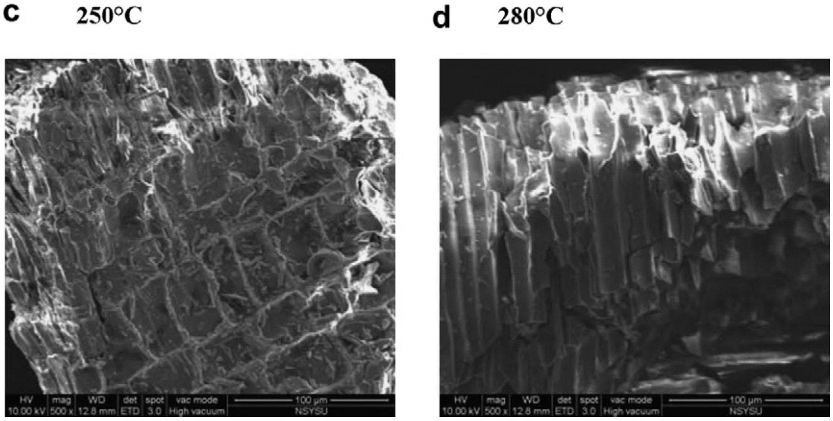
Fig. 6. Profiles of particle weight percentage from ground torrefied wood at the torrefaction temperatures of (a) 220, (b) 250 and (c) 280 °C (No. 1: >100 mesh; No. 2: 100–200 mesh; No. 3: 200–325 mesh; No. 4: <325 mesh).



a Raw wood

b 220°C

HV mag WD det spot vac mode 100 μm
10.00 kV 500 x 12.5 mm ETD 3.0 High vacuum NSYSU
HV mag WD det spot vac mode 100 μm
10.00 kV 500 x 12.8 mm ETD 3.0 High vacuum NSYSU



c 250°C

d 280°C

HV mag WD det spot vac mode 100 μm
10.00 kV 500 x 12.8 mm ETD 3.0 High vacuum NSYSU
HV mag WD det spot vac mode 100 μm
10.00 kV 500 x 12.8 mm ETD 3.0 High vacuum NSYSU

Fig. 7. SEM images (×500) of (a) raw wood and torrefied woods at the torrefaction temperatures of (b) 220, (c) 250 and (d) 280 °C (particle size > 100 mesh and torrefaction time = 1 h).

tends to be pronounced, especially at the torrefaction conditions of 280 °C and 2 h.

3.3. *Grindability of torrefied wood*

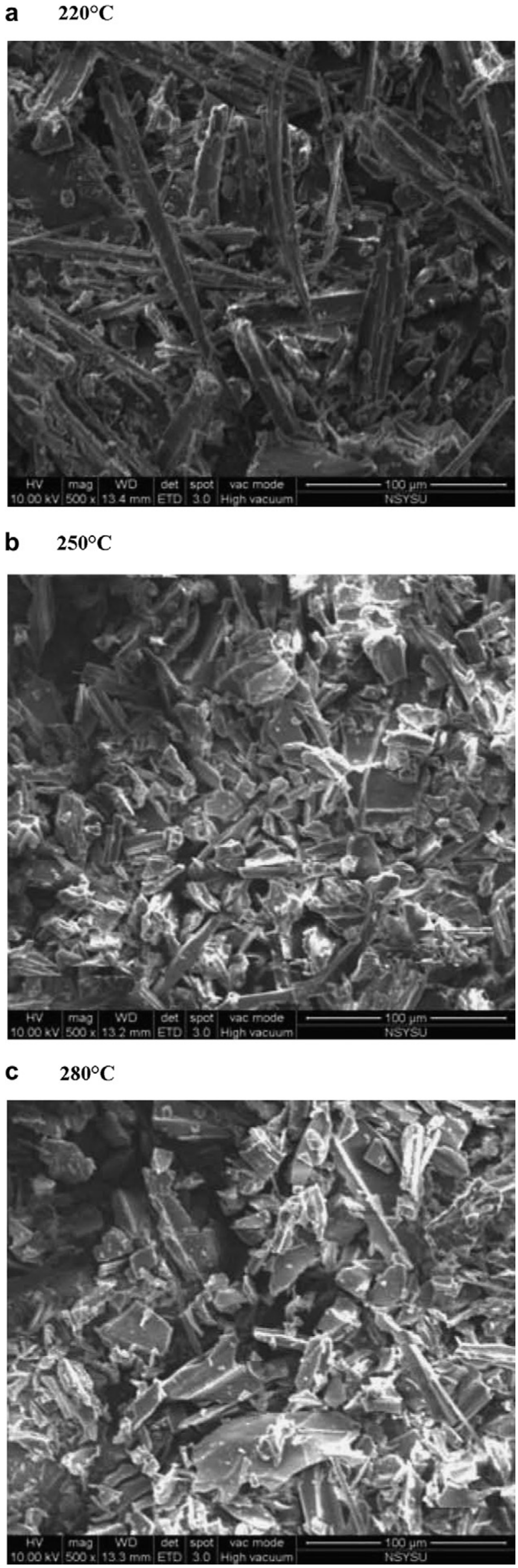
As described earlier, a standard procedure using the four-blade shedder cracker with 24,000 rpm for 1 min has been successfully developed to evaluate the grindability of the torrefied woods. By employing the procedure, the distributions of particle weight percentage in the four size regimes are displayed in Fig 6. With the torrefaction temperature of 220 °C, the weight percentage has a trend to decrease with decreasing particle size (Fig 6a), regardless of what the torrefaction time is. When the torrefaction temperature is 250 °C, the torrefaction time plays an important role in determining the size distribution. Specifically, with the torrefaction time of 0.5 h, a monotonic decrease in the distribution with decreasing size is exhibited (Fig 6b) which resembles the profiles at 220 °C. However, when the torrefaction time is elongated to 1 h, it can be found that the weight percentages of No. 1–3 decrease a bit, whereas the weight percentage of No. 4 increases to a certain extent. With the torrefaction times of 1.5 and 2 h, more small particles are produced in that No. 4 is raised markedly. Considering the torrefaction temperature of 280 °C, Fig 6c depicts that the weight percentage of No 1 is further decreased compared to those in Fig 6a and b. Similar to the behavior obtained in Fig 6b, once the torrefaction time is as long as 1.5 h, the weight percentage of No. 4 grows obviously. Summarizing the above observations, it is known that the grindability of the torrefied wood due to the torrefaction at 220 °C is almost independent of the torrefaction time and the grindability disadvantages the formation of smaller particles. Nevertheless, the grindability of the torrefied wood can be improved to a great extent at 250 and 280 °C if the torrefaction time is sufficiently long (>1 h) in that the weight percentage of small particle rises markedly.

3.4. *SEM observation*

To gain a deeper insight into the impact of the torrefactions on the wood, the scanning electron microscope (SEM) images of the raw wood and the ground torrefied woods at two different size regimes are shown in Fig 7 (No. 1) and Fig 8 (No. 2), respectively, where the torrefaction duration is 1 h. The images have been amplified by a factor of 500. Regarding the raw wood, as shown in Fig 7a, its surface is integrated (Fig 7a). In contrast, for the wood undergoing torrefaction, the thermal pretreatment has a pronounced impact on the wood surface. With the torrefaction temperatures of 220 and 250 °C, the surfaces of the wood are characterized by cell structures (Fig 7b and c). Following the torrefaction at 280 °C, the surface is further damaged so that the tubular-shape surface is exhibited (Fig 7d). When emphasis is placed on the particles whose size is between 100 and 200 mesh, it is observed that the shape of some particles from the torrefied wood at 220 °C is featured by filament (Fig 8a). However, once the torrefaction temperatures of 250 and 280 °C are performed, the particles tend to become spherical (Fig 8b and c). These observations are consistent with the study of Arias [23].

3.5. *Thermogravimetric analysis*

Thermogravimetric analysis (TGA) and Derivative Thermogravimetric (DTG) analysis of biomass in the environment of air are conducive to the evaluation of the biomass as a fuel. For this reason,


a 220°C
HV mag WD det spot vac mode 100 μm
10.00 kV 500 x 13.4 mm ETD 3.0 High vacuum NSYSU
b 250°C
HV mag WD det spot vac mode 100 μm
10.00 kV 500 x 13.2 mm ETD 3.0 High vacuum NSYSU
c 280°C
HV mag WD det spot vac mode 100 μm
10.00 kV 500 x 13.3 mm ETD 3.0 High vacuum NSYSU

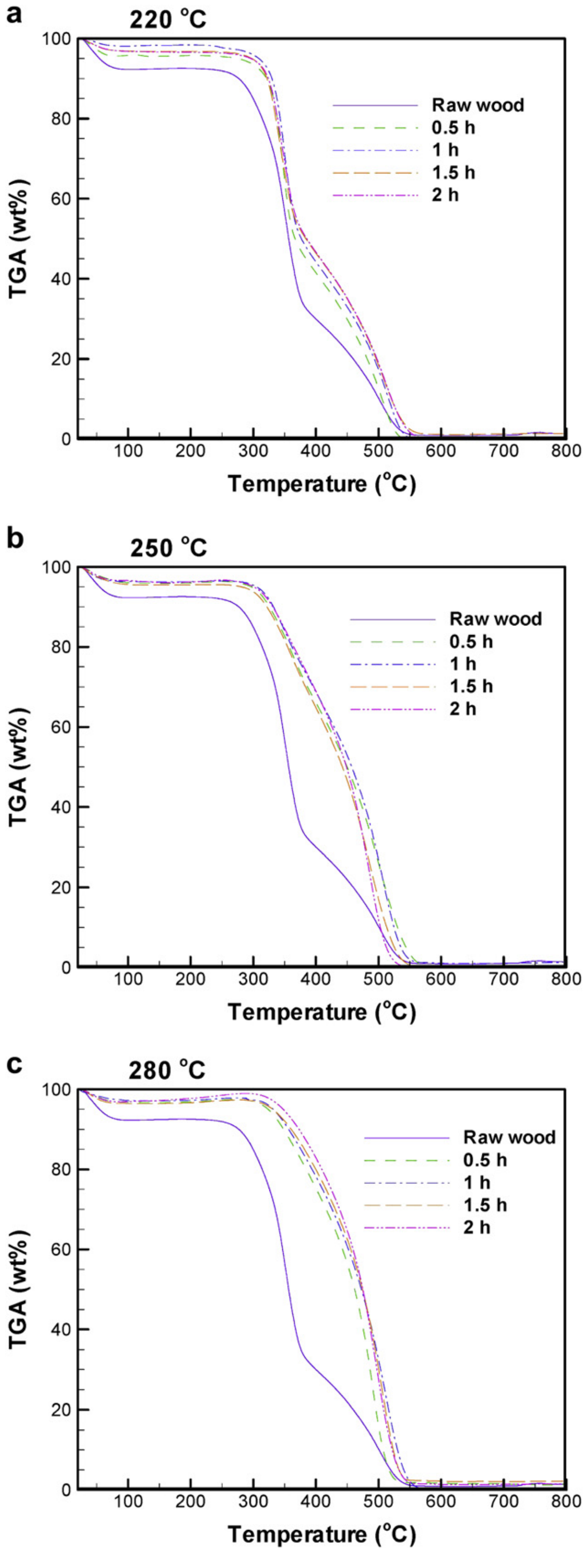


Fig. 9. Thermogravimetric analyses of raw wood and torrefied woods with the torrefaction temperatures of (a) 220, (b) 250 and (c) 280 °C.

Fig. 8. SEM images (×500) of torrefied woods at the torrefaction temperatures of (a) 220, (b) 250 and (c) 280 °C (particle size = 100–200 mesh and torrefaction time = 1 h).

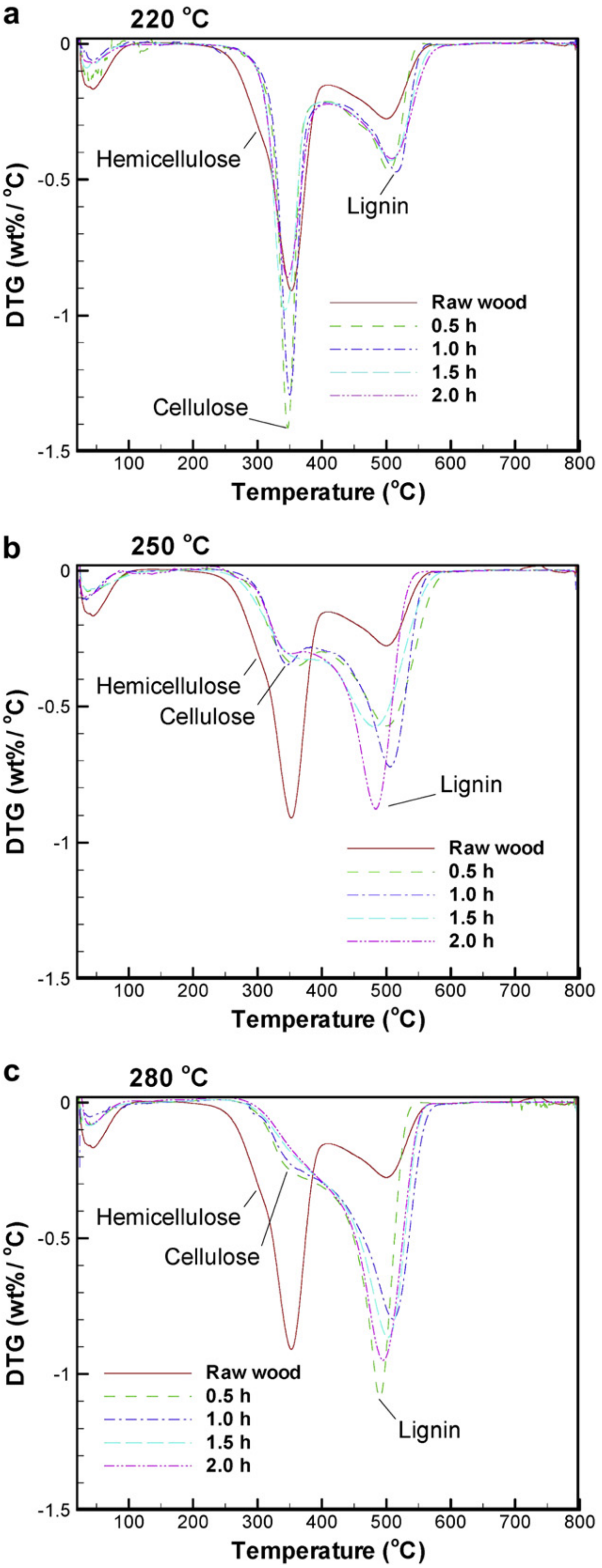


Fig. 10. Derivative thermogravimetric analyses of raw wood and torrefied woods at the torrefaction temperatures of (a) 220, (b) 250 and (c) 280 °C.

the distributions of TGA and DTG of the raw wood and torrefied materials are plotted in Figs 9 and 10, respectively. Upon inspection on the distributions of TGA, it is apparent that the thermal decomposition behavior of the raw wood is obviously different from those of the torrefied woods. The higher the torrefaction temperature, the more significant the difference between the raw wood and the torrefied ones (Fig 9). When the DTG curve of the raw wood is examined, the oxidations of hemicellulose, cellulose and lignin can be identified clearly (Fig 10a). Once the torrefaction temperature of 220 °C is performed, the double-peak distributions are observed (Fig 10b). The first and the second peaks correspond to the oxidations of cellulose and lignin, respectively. It is thus recognized that hemicellulose has been consumed obviously at the torrefaction temperature of 220 °C. When increasing the torrefaction temperature to 250 °C, the peaks of cellulose wither drastically (Fig 10b), indicating that cellulose is also consumed greatly with the aforementioned temperature. Once the torrefaction at 280 °C is carried out, the peaks of lignin is relatively pronounced and the peaks of cellulose almost disappear (Fig 10c). From the viewpoint of using torrefied wood as a fuel, it can be figured out that the energy is mainly contributed by cellulose and partly by lignin if the wood is torrefied at 220 °C. However, as the torrefaction temperature is no less than 250 °C, the role played by lignin in contributing the energy from burning the torrefied wood tends to become important.

3.6. Components of condensed liquid

Eventually, condensed liquids stemming from the three torrefactions are analyzed and the chromatograms of GC-MS analysis are provided in Fig 11 where the main components in the liquids are identified in the figures and illustrated in Table 3. As seen in Table 3,

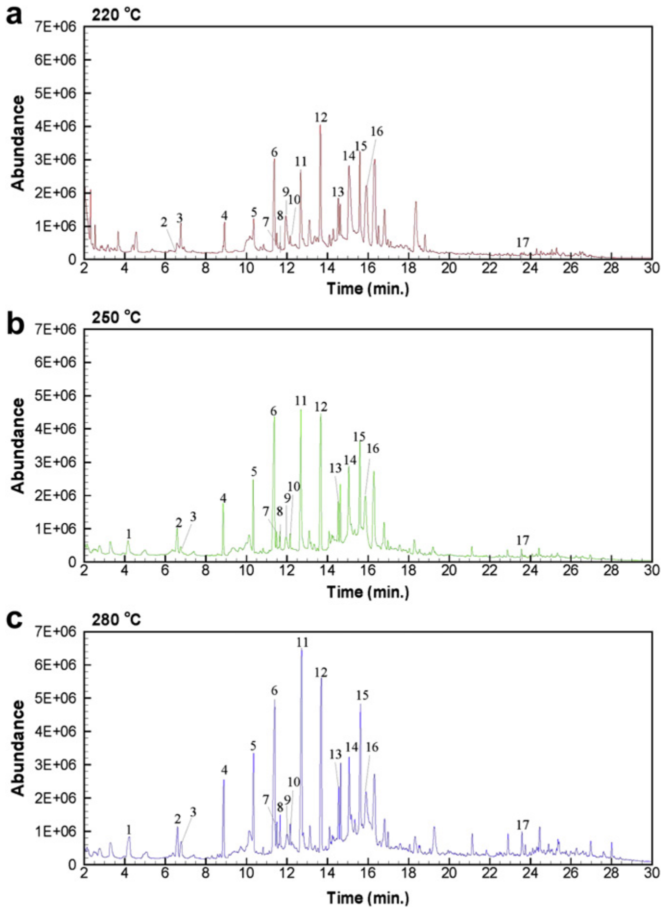
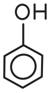
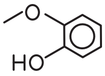
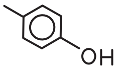
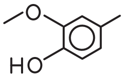
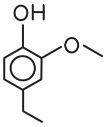
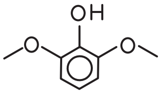
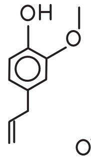
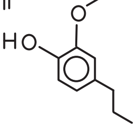
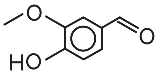
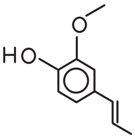
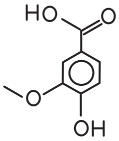
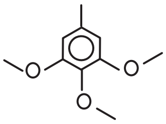
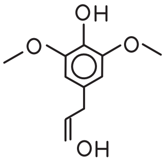
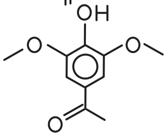
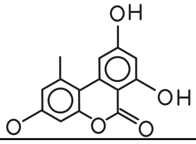


Fig. 11. Chromatograms of condensed liquid from the torrefactions at (a) 220, (b) 250 and (c) 280 °C with 2 h.

Table 3
Main components contained in condensed liquid from wood (Lauan) torrefaction.

No.	Name	Structure	Formula
1	Phenol		C_6H_6O
2	2-methoxyphenol		$C_7H_8O_2$
3	4-methylphenol		C_7H_8O
4	2-methoxy-4-methylphenol		$C_8H_{10}O_2$
5	4-ethyl-2-methoxyphenol		$C_9H_{12}O_2$
6	2,6-dimethoxyphenol		$C_8H_{10}O_3$
7	2-methoxy-4-prop-2-enylphenol		$C_{10}H_{12}O_2$
8	2-methoxy-4-propylphenol		$C_{10}H_{14}O_2$
9	4-Hydroxy-3-methoxybenzaldehyde		$C_8H_8O_3$
10	2-methoxy-4-[(1E)-prop-1-en-1-yl]phenol		$C_{10}H_{12}O_2$
11	4-hydroxy-3-methoxybenzoic acid		$C_8H_8O_4$
12	1,2,3-trimethoxy-5-methylbenzene		$C_{10}H_{14}O_3$
13–15	2,6-dimethoxy-4-prop-2-enyl-phenol		$C_{11}H_{14}O_3$
16	1-(4-hydroxy-3,5-dimethoxyphenyl)ethanone		$C_{10}H_{12}O_4$
17	7,9-dihydroxy-3-methoxy-1-methyl-6H-dibenzo[b,d]pyran-6-one		$C_{15}H_{12}O_5$

it can be found that most of the species are monoaromatics, such as phenol (1), 2-methoxyphenol (2), 4-methylphenol (3), 2,6-Dimethoxyphenol (6), eugenol (7) and vanillin (9). As a whole, the intensity of the peaks in the chromatogram increases as the torrefaction temperature increases, especially for 4-hydroxy-3-methoxybenzoic acid (11) whose growth is much more notable than others. In addition, it is noteworthy that increasing torrefaction temperature increases the yields of heavier components. For instance, the compound of 7,9-dihydroxy-3-methoxy-1-methyl-6H-dibenzo[b,d] pyran-6-one (17), which pertains to a heterocyclic hydrocarbon, was detected at the retention time of 23.59 min. The higher the torrefaction temperature, the higher the peak. Seeing that many aromatics are detected from the condensed liquids, it is better to treat them as chemicals rather than as fuels, from the viewpoint of practical utilization, as observed.

4. Conclusions

Thermal pretreatments of woody biomass (Lauan) blocks via torrefaction at various temperatures and times have been studied. Particular emphases were focused on the influence of the torrefaction upon the properties of the wood blocks and the formation of condensed liquid. It was found that increasing torrefaction temperature or time intensified the carbon content and calorific value of the wood blocks; the liquid yield was increased as well. However, once the torrefaction temperature was as high as 280 °C, the weight loss of the wood became drastic (>50%). It is thus believed that the temperature of 280 °C was not a proper condition for biomass torrefaction even though the calorific value of the torrefied wood was amplified up to 40%. The distributions of TGA and DTA suggested that the oxidation of the wood was mainly contributed by cellulose and lignin if the wood was torrefied at 220 °C. Increasing torrefaction temperature (e.g. 250 and 280 °C) intensifies the reaction of cellulose, hence using the torrefied wood as a fuel turns to be contributed by lignin to a great extent. In this study, a standard procedure for testing the grindability of the torrefied woods has also been developed. From the procedure, the tests indicated that the grindability of the woody biomass was able to improve apparently if the wood blocks were torrefied at the temperature as high as 250 °C and the time longer than 1 h. An examination of liquid formation revealed that over 50% of consumed wood was transformed into liquid, no matter what the torrefaction temperature and time were. This implies that the gas stream from the torrefaction could be condensed to recover liquid. The principal components in the condensed liquids were monoaromatics; little amount of heterocyclic hydrocarbons were also contained. Abundant aromatics contained in the liquids imply that they can be treated as chemicals rather than as fuels.

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